



# Biochar from oil palm biomass: A review of its potential and challenges



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## ABSTRACT

Climate change, food crisis, energy generation and environmental pollution are among the greatest threats and challenges faced by mankind today. Biochar production from various biomass sources has gained a lot of interests since its addition to degraded agricultural soils not only improve soil fertility and biomass yield, but also mitigate climate change through soil carbon sequestration and reduction in greenhouse gas emissions. There are enormous amounts of oil palm biomass generated along with the main palm oil production streams. A lot of research has been carried out to convert oil palm biomass into value-added products, but none except biochar has come close to be labeled as carbon negative products. In this paper, a review about production and application potential of biochar from oil palm biomass in Malaysia is given. Besides, some of the challenges in promoting biochar production and application, such as nature of the feedstocks, economic and logistical factors and market acceptance are highlighted as well. Producing biochar from oil palm biomass can potentially lead to a healthier environmental, societal and economic growth for the oil palm industry specifically, and enhances sustainability in worldwide context.

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## 1. Introduction

Production of biochar from various biomass resources and its application to low fertility soils are attracting significant attention

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globally due to its unique potential to improve soil nutrient retention capacity, water holding capacity and act as stable carbon sink to mitigate climate change and reduce greenhouse gas (GHG) emissions [1–3]. Biochar is a carbonaceous material obtained from the pyrolysis of biomass under zero or limited supply of oxygen and at relatively low temperature, usually below 700 °C [2,4]. Biochar is beneficially applied to low fertility soils to increase crops yield, in contrast to conventional charcoal which is optimized for heat and power generation [5,6], anodic material for Li-ion batteries [7], biocement production [8] and activated carbon for pollutant removal from gaseous and aqueous emissions [9]. In addition, the heat and energy generated as part of the biochar production has potential to substitute non-renewable fossil fuels.

Malaysia is strengthening its oil palm production with the increasing global demand for edible oil, biodiesel and oleochemicals derived from palm oil. Total exports of palm oil and palm oil products reached 14.7 million t in 2010 contributing US \$ 4500 million income to the country [10]. However, the oil extraction rate is only about 10% from the palm oil production with the majority 90% left as biomass [11]. For each kg of palm oil extracted, there are roughly another 4 kg of dry biomass generated, of which a third is found in fresh fruit bunch (FFB) derived by-products e.g., empty fruit bunch (EFB), palm kernel shell (PKS) and mesocarp fiber (MF), and the other two third is represented by oil palm trunk (OPT) and oil palm frond (OPF) inside the plantation estates [12]. The palm oil industry has come under increased pressure from Western countries under the Renewable Fuel Standard (RFS2) Program (United States Environmental Protection Agency) and the European Union's Renewable Energy Directive (EU RED) to ensure that the crude palm oil (CPO) production stream is sustainable without harming the environment and natural resources [13–16]. With the projected growth in oil palm via biotechnological advances to increase oil palm productivity and less expansion on oil palm cultivation, the disposal of these huge amounts of residues is creating challenges but also new opportunities.

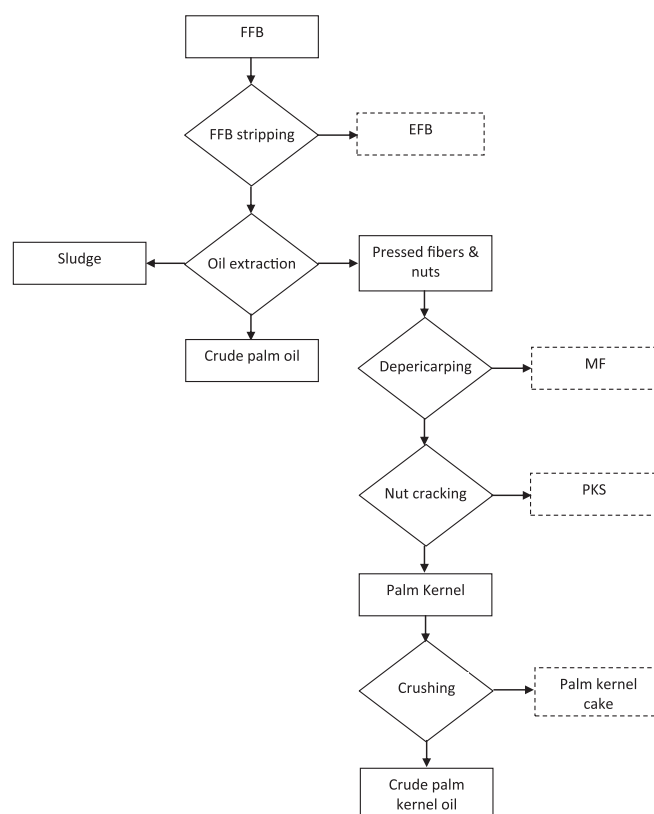
Extensive research has been undertaken to develop value-added products, for example paper pulp from EFB [17–19], bioethanol from EFB and OPT [20–25], furniture from OPT [26–28], organic fertilizer from EFB and palm oil mill effluent (POME) [29–32] and renewable energy [33–34]. However, limited research has been carried out with focus on the utilization of oil palm biomass for biochar production. The objective of this paper is to review the potential of biochar production in Malaysia with the abundance of oil palm biomass available. Biochar production along with the abundance of readily available oil palm biomass opens the door for the country to mitigate climate change, improve less fertile soils and increase crops yield.

## 2. Oil palm biomass in Malaysia

The oil palm was first brought to Southeast Asia in 1848, when four seedlings, originating from West Africa, were planted in the botanical gardens at Buitenzorg (now Bogor) in Java. By 1919, there were more than 6000 ha of oil palm plantation in Sumatra (Indonesia), rising to 32,000 ha in 1925, by which time 3400 ha had been planted in Malaya (now Malaysia) [35]. The replanting of old rubber estates with oil palm trees in the early 1960s under Federal Land Development Authority (FELDA) smallholder schemes had caused a rapid development in oil palm plantation in Malaysia [35]. Currently, Malaysia is one of the world leading producers of palm oil. Based on the latest statistic (April 2014) shown by Malaysian Palm Oil Board (MPOB) [36], planted mature and immature oil palm trees cover a total of 5.230 million ha representing 79% of the total area (6.6 million ha, 2009) designated for agriculture and 15% of overall Malaysian territory [11].

Solid oil palm biomass by-products are generated throughout the year as EFB, MF, and PKS in palm oil mills (Fig. 1), as well as OPT and OPF at oil palm plantations. The FFB contains about 21% CPO, 6–7% palm kernel, 13.5–15% MF, 5.5–7% PKS and 22–23% EFB [11,37–39]. Assuming an average annual yield of FFB of 20.1 t ha<sup>-1</sup> containing 19.7% recoverable CPO, 23 million t of EFB, 12.1 million t MF and 8.0 million t PKS (all in wet basis) are generated in Malaysia per year [39]. Replanting of oil palm tree is done in 25 years intervals due to the decrease in fruits yield and oil productivity [25]. Pruning of OPF is needed in order to allow cutting of ripe fruit branches during harvesting [40] which generates an approximate of 44 million t of the dried pruned OPF per annum [41]. During replanting season, up to 75 t ha<sup>-1</sup> and 15 t ha<sup>-1</sup> dry matter of OPT and OPF respectively are chipped and left in the field as mulch [11,41]. The availability of dried OPT and OPF a year based on an estimated 5% oil palm planted area due for replanting is 18 and 4 million t, respectively.

Biomass is made up of cellulose, hemicellulose, lignin, extractives and inorganics (ash) with different physical and chemical



**Fig. 1.** Flow chart for generation of solid biomass by-products in palm oil mills (dashed line boxes). FFB – fresh fruit bunch, EFB – empty fruit bunch, MF – mesocarp fiber, and PKS – palm kernel shell.

**Table 1**  
Oil palm biomass chemical components and heating value [41,42]

| Types of biomass  | Heating value (MJ kg <sup>-1</sup> dry wt.) | Chemical components (% dry wt.) |                |        |             |     |
|-------------------|---|---------------------------------|----------------|--------|-------------|-----|
|                   |   | Cellulose                       | Hemi-cellulose | Lignin | Extractives | Ash |
| Mesocarp fiber    | 19.06                                       | 33.9                            | 26.1           | 27.7   | 6.9         | 3.5 |
| Empty fruit bunch | 18.88                                       | 38.3                            | 35.3           | 22.1   | 2.7         | 1.6 |
| Palm kernel shell | 20.09                                       | 20.8                            | 22.7           | 50.7   | 4.8         | 1.0 |
| Oil palm trunk    | 17.47                                       | 34.5                            | 31.8           | 25.7   | 3.7         | 4.3 |
| Oil palm frond    | 15.72                                       | 30.4                            | 40.4           | 21.7   | 1.7         | 5.8 |

properties due to its diverse origin and species. Cellulose with a molecular weight of about 100,000 is a polymer with linear chains of glucopyranose units linked to each other by its 1,4 carbon atoms in the  $\beta$ -configuration [42]. The second major constituent with lower molecular weight, hemicellulose, is a mixture of various polymerized monosaccharides such as glucose, mannose, galactose, xylose, arabinose, methyl glucuronic acid and galacturonic acid residue [43]. Lignin, a highly branched polymer attached with polysaccharides, is composed of phenyl propane based monomeric units linked together by several types of ether linkages and also various kinds of carbon-carbon bonds [44]. Table 1 [41,42] tabulates the chemical compositions and heating value of each type of oil palm biomass.

### 2.1. Current practices and potential applications

Currently, oil palm biomass is converted into various value-added products via different available conversion technologies or conventional practices. Palm oil mills in Malaysia use  $98.4 \pm 1.0\%$  of MF and  $62.4 \pm 15.9\%$  PKS as source of fuel for the boilers to generate electricity and steam for palm oil extraction while unused MF (1.6%) and PKS (37.6%) are sold as fuel in the market [39]. The high moisture content of more than 65% in EFB requires substantial amount of thermal energy for drying prior to combustion, thus reducing the energy efficiency [42] which may explain why palm oil mills largely refrained from using EFB as fuel. Two notable exceptions are EFB-based grid-connected power plants in Sabah i.e. Kina Biopower Sdn. Bhd. and Seguntor Bioenergy Sdn. Bhd. In addition, alkali content in EFB mainly potassium and sodium, can create serious slagging and fouling in conventional boilers causing power plant shutdowns for maintenance and thus economical losses [45].

The oil palm ash (OPA) from the boiler, amounting to 0.31% of FFB or  $62.3 \text{ kg}_{\text{FFB}} \text{ ha}^{-1} \text{ yr}^{-1}$ , is fully used as fertilizer [39] since it has very low level of toxicity and high amount of potassium [15,46]. The presence of silica in the OPA makes it also suitable to be mixed with cement but preferably in low weight percentage as the organic components may inhibit the setting of cementitious processes [46].

OPT and OPF ( $3 \text{ t}_{\text{OPT+OPF}} \text{ ha}^{-1} \text{ yr}^{-1}$ ) as well as EFB ( $4.6 \text{ t}_{\text{EFB}} \text{ ha}^{-1} \text{ yr}^{-1}$ ) or  $49 \text{ kg}_{\text{ash}} \text{ ha}^{-1} \text{ yr}^{-1}$  are extensively used for mulching to return nutrients back to the soil [11,39,47]. Nevertheless, mulching of the biomass should be controlled to prevent oil palm pests [48]. In addition, OPF is used to feed herbivore livestock [49]. In some cases, excess PKS are used for road surfacing in estates [40], while surplus EFB is land-filled, creating considerable pollution and economical problems.

Diverged research and development works have expanded the options for utilization of oil palm biomass to other industries. Varieties of pulping methods have been explored with these abundant, inexpensive and renewable fibrous sources for paper-making [50]. Zealway Corporation has built the first EFB pulping plant in Malaysia in 2008 producing fluting medium paper [17]. SEA Pacific Paper Tech Sdn. Bhd. in Kamunting, Perak has since 2008 modified its EFB-pulp mill and is currently producing PALMOR™ EFB-pulp for brown paper making [51]. 1Green Enviro Sdn. Bhd. has developed a patented technology using raw EFB to produce better pulp fibers (recycled bleached mechanized pulp) than existing methods in an effort to substitute softwood-corrugating carton pulp [52]. 1Green Enviro is set to construct the largest integrated pulp-and-paper mill in the world located in Jempol, Negeri Sembilan, Malaysia that can produce up to 70,000 metric t of industrial brown paper a year using EFB as the main raw material [52]. Other commercial exploitation currently in the pipeline is the commissioning of an integrated pulp and paper plant (consisting of a pulp plant, a biomass co-generation plant, a

palm oil mill effluent biogas plant and a palm oil mill) at Kunak, Tawau, Sabah, Malaysia by Eko Pulp and Paper Sdn. Bhd. The pulp and paper mill has capacity to produce up to 30,000 t of pulp a year [53].

EFB has also been found suitable in production (by pre-carbonization) of self-adhesive carbon grains (SACG) that can be pelletized without the presence of any binding agent for activated carbon pellets production [54]. On the other hand, by adding a binding agent, for example rubber latex, the EFB can be used as cushion filling material [55]. Many Malaysia-based companies (> 15) have been involved in fiber processing from EFB – producing long EFB fibers for various product applications such as cushion and rubberized mattress, and short EFB fibers for briquettes [56] and pellets as a fuel. Companies that are actively involved include QL Resources Bhd. (Tawau, Sabah), Global Green Synergy Sdn. Bhd. (Bidor, Perak), Detik Aturan Sdn. Bhd. (Seri Kembangan, Selangor), HK Kitaran Sdn. Bhd. (Pulau Penang), FNI Biofuel Sdn. Bhd. (Semenchu, Johor), DRPTS Manufacturing Sdn. Bhd. (Melaka), etc.

OPT can be converted into saw-wood, medium density fiberboard (MDF), plywood or lumber for manufacturing furniture [12,27,28,34]. The strength of the plywood made from OPT is comparable to commercial plywood [12]. To date, four companies (Kimmu Trading Sdn. Bhd., I.K. Panel (M) Sdn. Bhd., Emas Cergas Express, FAZA Solutions) in Malaysia produce OPT-based plywood [pers. comm.]. On the other hand, the production of MDF from OPT as part of the ingredients was successfully commercialized in 2012 by the Malaysian Palm Oil Board (MPOB) and Dongwha Fiberboard Sdn. Bhd. [57] although OPF was also found as a suitable ingredient. Besides, OPF is also used for manufacturing composite boards by adding binding agents such as phenol and urea formaldehyde resins [58].

Old OPT and EFB can be a promising source of sugars for bioethanol production as a second generation biofuel which is generated from non-edible cellulosic biomass [21–22,24–25,44,59,60]. In December 2010, Sime Darby (SD) Research Sdn. Bhd. and Mitsui Engineering and Shipbuilding Co. Ltd. (MES) constructed and operated the world's first demonstration plant next to SD Tennamaram Palm Oil Mill to produce second generation bioethanol from EFB using MES's and Denmark's Inbicon technology (hydrothermal pretreatment and enzymatic hydrolysis methods) [61]. The plant was dismantled and shifted to Teck Guan Group, Tawau, Sabah in June 2013 for full-scale demonstration [pers. comm.]. Besides, the Chinese government is planning to finance the joint venture between Malaysian company Lestari Pasifik Bhd. and Russian company Arter Group to build 616 biorefinery plants for biofuel production from second generation bioethanol in Malaysia and Indonesia [60].

Char obtained from pyrolysis of MF at  $850^\circ\text{C}$  and 3.5 h holding time shows high fixed carbon and relatively low ash content, which is a favorable precursor for preparing activated carbon [62]. This activated carbon can be used to prepare carbon molecular sieve (CMS) via carbon deposition [55]. CMS is a material containing precise and uniform size of tiny pores which is used as an adsorbent for gases and liquids, normally to separate nitrogen from the other gases contained in air [12]. Besides, the commercial trial production of activated charcoal via closed brick carbonization system (M-Trex Active Carbon, Hutan Melintang, Perak) and Taki carbonization system (MPOB Kluang Research Station, Johor) have been commissioned since 2011 to produce not just PKS-based charcoal but with wood-vinegar and bio-oil being other main products [pers. comm.]. The other active commercial site is at Seri Langat Palm Oil Mill, Selangor [pers. comm.].

With the rapid growth of palm oil production, the palm oil industry is increasingly dealing with the sustainability of the production stream to ensure a viable future for the whole industry.

The industry needs to show continuous efforts in creating zero waste operations by utilizing its by-products for continuous sustainable growth. Such efforts do not only generate extra income, but also create a promising new industry and employment. From the review above it can be concluded that the palm oil industry is reusing most of its PKS and MF as in-house fuel, while OPT, OPF and EFB are used as fertilizer or raw material for plywood, bioethanol and pulp paper production. However, to transform into a carbon-neutral or ultimately carbon-negative industry the conventional reuse of its by-products is insufficient because all biomass fixed carbon is released back into the atmosphere as GHG CO<sub>2</sub>. Continuous R&D efforts are therefore vital to improve the technical and environmental performance, reduce cost, achieve social acceptability of new technologies and identify better solutions to transform this biomass into a more valuable end product. A promising path towards carbon-neutrality on the one hand and improved crop productivity on the other is by converting solid palm oil by-products into biochar through a thermochemical process – pyrolysis.

### 3. Pyrolysis in Malaysia

Various pyrolysis reactors have been developed mostly in lab-scale which include bubbling fluidized bed, transport bed, circulating fluidized bed, rotating cone, vacuum pyrolysis reactor, ablative reactor and screw reactor as summarized in Table 2 [63,64]. Since the 1990s, a number of large-scale pyrolysis plants have been established in Malaysia, with more focus still on the bio-oil and energy production. For example, a collaboration between Genting Sanyen Bhd. and Biomass Technology Group (BTG) from The Netherlands in 2005 has started the first commercial bio-oil plant (currently not in operation) in Malaysia with the production of 2 t bio-oil h<sup>-1</sup> from EFB [12]. The second pyrolysis plant in Malaysia is a tire recycling plant where scrap tires are broken down into char (30%), recovered oil (50%),

pyrolysis gas (10%) and steel wires (10%). The plant can handle up to 120 t tires day<sup>-1</sup> and all the end products are exported to Korea [65]. Recently, the National Key Economic Areas (NKEA) on palm oil sector aims to establish 9 bio-oil plants by 2015 and 29 bio-oil plants by 2020 throughout the country. The first plant will be built in FELDA Sahabat, Sabah which will use EFB to produce bio-oil [33,66]. The other company, Palm Oligo Sdn. Bhd. constructed a 5 t day<sup>-1</sup> fast pyrolysis plant using palm kernel cake (PKC) for bio-oil production starting in 2012 [pers. comm.]. To date, the plant has been scaled up to a commercial plant and is operated by Lipochem (M) Sdn. Bhd.

Despite the focus on bio-oil production through fast pyrolysis process, the importance of slow pyrolysis process to enhance yield of biochar should be considered if we are serious about climate change mitigation and improving soil fertility. Universiti Putra Malaysia (UPM) has taken the first step by collaborating with NASMECH Technology Sdn. Bhd. in the EFB Carbonator™ project with the ability to process up to 20 t EFB a day for biochar production [67].

#### 3.1. Pyrolysis process design

Pyrolysis represents a potential route to upgrade the oil palm biomass into a value-added carbonaceous material – biochar and renewable fuels. During pyrolysis, biomass is thermally decomposed to biochar, bio-oil and syngas under low or zero oxygen conditions. Pyrolysis processes can be categorized as slow pyrolysis and fast pyrolysis [68]. Slow pyrolysis yields relatively more biochar but less bio-oil with about 35% of the feedstock carbon ending up as biochar, 30% as bio-oil and 35% as syngas [68]. As for fast pyrolysis, it gives yield of about 15% biochar, 70% bio-oil and 13% syngas [69]. Modes of pyrolysis and distribution of product yield are shown in Table 3 [70]. The yield and composition of final pyrolysis products are dependent on various parameters, including temperature, residence time, feedstock used, reactor

**Table 2**  
Description of various pyrolysis reactors [63,64]

| Pyrolysis reactor            | Process  |
|------------------------------|--|
| Fluidized bed                | The feedstock is blown into a bed of heated sand to be mixed instantly. Close packing of sand and biomass secure rapid heat transfer and conversion. |
| Ablative reactor             | The feedstock is pressed against a heated metal disc. The disc is rotating at high speed, melting the biomass.                                       |
| Twin screw reactor           | Two parallel screws rotating at high speed, transporting and mixing heated sand and biomass.   |
| Pyrolysis centrifuge reactor | The feedstock is blown into a heated high speed centrifuge. Biomass is transported and converted along the inner surface of the heated shell.        |

**Table 3**  
Modes of pyrolysis and distribution of major products [70]

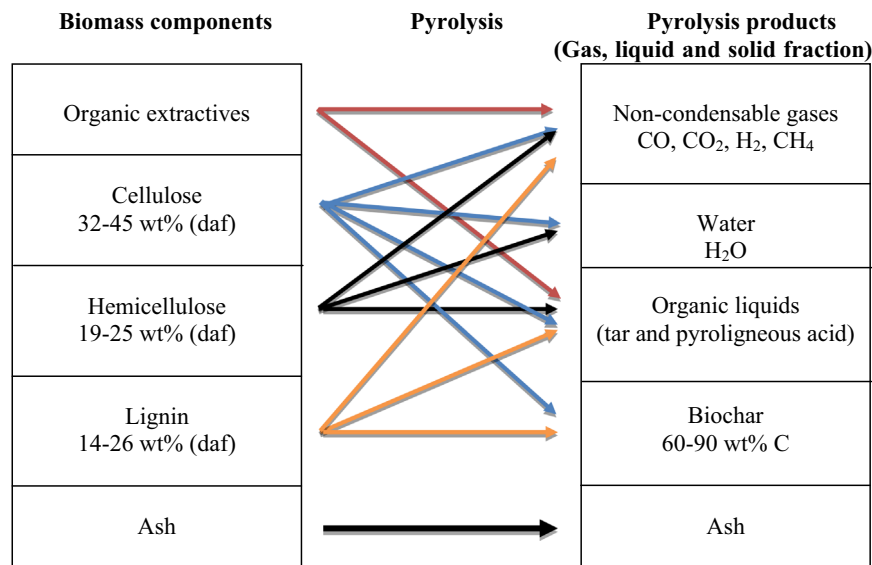
| Mode                 | Conditions  | Solid (%) | Liquid (%) | Gas (%) |
|----------------------|---|-----------|------------|---------|
| Fast                 | Reactor temperature 500 °C<br>Very high heating rate > 1000 °C s <sup>-1</sup><br>Short hot vapor residence ~1 s          | 12        | 75         | 13      |
| Intermediate         | Reactor temperature 400–500 °C<br>Heating rate range 1–1000 °C s <sup>-1</sup><br>Hot vapor residence ~10–30 s            | 25        | 50         | 25      |
| Slow – torrefaction  | Reactor temperature ~290 °C<br>Heating rate up to 1 °C s <sup>-1</sup><br>Solid residence time ~30 min                    | 77        | 0–5        | 23      |
| Slow – carbonization | Reactor temperature 400–500 °C<br>Heating rate up to 1 °C s <sup>-1</sup><br>Long solid residence time from hours to days | 33        | 30         | 35      |

**Table 4**

Summary of pyrolysis of oil palm biomass.

| Process description   | Pyrolysis product (s) investigated | References |
|---|------------------------------------|------------|
| Slow pyrolysis of EFB under vacuum at 280 °C and followed by further carbon activation.   | Char                               | [54]       |
| Pyrolysis of MF in a bench-scale stainless steel vertical reactor at temperatures of 450–950 °C for holding times of 0.5–4.5 hours and heating rates of 5–20 °C min <sup>−1</sup> .   | Char                               | [62]       |
| Pyrolysis of palm oil by-products (PKS, MF and EFB) in thermogravimetry analyzer (TGA) up to 900 °C.  | Gas                                | [72]       |
| Fast pyrolysis of PKS in a fluidized bed reactor pyrolysis plant with various temperatures, feed sizes and feed rates.  | Bio-oil (major product), gas, char | [77]       |
| Slow pyrolysis of oil palm pressed MF in a laboratory-scale pyrolyzer at terminal temperatures of 450–800 °C and a heating rate of 10 °C min <sup>−1</sup> .  | Char (major product), bio-oil      | [78]       |
| Pyrolysis of PKS and palm kernel cake in a fixed-bed pyrolyzer at temperatures 500 and 700 °C with heating rates of 5 and 10 °C min <sup>−1</sup> .   | Char, bio-oil, gas                 | [79]       |
| Pyrolysis of palm oil by-products (PKS, MF, EFB) in a bench-scale countercurrent fixed bed at temperatures 500–900 °C, various residence times and catalyst adding.   | Gas                                | [80]       |
| Pyrolysis of PKS in a bench-scale stainless steel vertical reactor at temperatures of 400–900 °C, holding times of 0.5–3.0 hours, heating rates of 5–50 °C min <sup>−1</sup> and N <sub>2</sub> flow rates of 50–300 cm <sup>3</sup> min <sup>−1</sup> for further carbon activation. | Char                               | [84]       |
| Pyrolysis of EFB in the quartz fluidized-fixed bed reactor at various temperatures, particle sizes and heating rates.   | Bio-oil (major product), char, gas | [85]       |
| Pyrolysis of PKS and OPF in a TGA at different temperatures.  | Hydrogen                           | [86]       |
| Fast pyrolysis of wash and unwashed EFB in fluidized bed bench-scale reactor.   | Bio-oil                            | [87]       |

EFB - empty fruit bunch; MF - mesocarp fibre; PKS - palm kernel shell

**Fig. 2.** Schematic pattern of biomass decomposition via pyrolysis [64].

configuration, heating rate, operating pressure and addition of catalyst [5,71–74].

### 3.2. Pyrolysis parameters

Pyrolysis is an endothermic process as shown exemplary for wood at 400 °C [75].

Biomass ( $2C_{42}H_{60}O_{28}$ ) + heat → tarry vapors/bio-oil ( $C_{28}H_{34}O_9$ ) + gas ( $28H_2O + 5CO_2 + 3CO$ ) + char ( $3C_{16}H_{10}O_2$ ).

Each of the pyrolysis parameters – temperature, residence time, heating rate, particle size, inert gas flow rate and type of reactor,

gives different final pyrolysis products yield. Temperature and residence time are among the most critical operating parameters [76,77].

An increase in the final temperature and residence time results in a reduction of biochar yield due to gasification of the solid biochar [62,78–79]. With increasing temperature up to 500 °C, maximum bio-oil yield can be achieved, however, the yield drops with further increase in temperature [73,77]. In contrast, gas products are favored at high temperature and long residence time as expected due to the quantity of volatiles evolved increase with increasing temperature [72,78,80]. The gas consists mainly of H<sub>2</sub>,



CO<sub>2</sub>, CH<sub>4</sub> and CO [43,72,79]. The yields of H<sub>2</sub> and CO increase with temperature, but the yields of CO<sub>2</sub>, CH<sub>4</sub> and H<sub>2</sub>O decrease and essentially become zero at temperature exceeds 800 °C [72,80]. Table 4 provides a summary of research on oil palm biomass pyrolysis over the past two decades [55,62,72,77–87].

### 3.3. Biomass feedstocks and main reactions

Hemicellulose, cellulose and lignin react in various ways at different temperatures to give different distribution of pyrolysis products [70]. Among these three major compositions of biomass, hemicellulose is the easiest to be pyrolyzed at temperature between 200 and 350 °C due to its branched polymer structure with short side chains [88]. Cellulose with its semicrystalline array chains associated with one another making it thermally more stable to decompose at 305–375 °C [86]. As for lignin which decomposes steadily over 250–500 °C, it is a complicated structure of phenolic polymers encasing the polysaccharides of the cell walls that produces strong and durable composite materials [89]. Khor et al. [78] conducted slow pyrolysis experiments with oil palm pressed MF in a laboratory-scale reactor and correlated the observed weight losses at 200–300 °C, 300–400 °C and 200–900 °C to hemicellulose, cellulose and lignin decomposition, respectively.

According to Antal and Grønli [75], Haykiri-Acma et al. [90] and Thomsen et al. [64], cellulose and hemicellulose are the constituents in biomass that give most of the volatile products during pyrolysis, while lignin content is mainly responsible for the production of biochar. Fig. 2 shows a schematic pattern of biomass decomposition via pyrolysis [64].

## 4. Benefits and challenges of production and applications of biochar

### 4.1. Biochar for GHG mitigation

The Fourth Assessment Report (AR4) of the United Nations Intergovernmental Panel on Climate Change (IPCC) concluded that “Most of the observed increase in global average temperature since the mid-20th century is very likely due to the observed increase in anthropogenic GHG concentrations. There is high agreement and much evidence that with current climate change mitigation policies and related sustainable development practices, global GHG emissions will continue to grow over the next few decades” [91]. Human activities lead to emissions of four long-lived GHGs which are carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), nitrous oxide (N<sub>2</sub>O) and halocarbons [91]. When emissions occur at a faster rate than those of the removal processes, atmospheric concentrations of GHG increase accordingly.

CO<sub>2</sub> is absorbed by plants as they grow. If the CO<sub>2</sub> (released during combustion or natural mineralization processes) can be captured and stored geologically, CO<sub>2</sub> will be removed from the atmosphere into long term storage [92]. The conversion of biomass carbon to biochar leads to sequestration of about 50% of the initial carbon compared to the low amounts retained after burning (3%) and biological decomposition (less than 10–20% after 5–10 years) [93]. Hence, biochar incorporated into agricultural soil can help to mitigate climate change through stable carbon storage and reduction of GHG emissions. Lehmann et al. [93] and Mathews [94] estimated that up to 4 gigatonnes of carbon can potentially be removed per year, which is equivalent to the carbon flux currently created through burning of all fossil fuels.

Pyrolysis of biomass to produce biochar results in biochar being labeled as net-negative carbon product as carbon is sequestered instead of releasing the carbon into the atmosphere [95]. Besides biochar, syngas and bio-oil are produced during the pyrolysis

process thus providing additional energy production [96,97]. While biochar from oil palm biomass acts as a carbon sink, it also retains energy that is unavailable for palm oil mill operation. A new integrated system coupled with economical energy mix must therefore be identified. For example, capture and combustion of biogas from POME not only results in a reduction of GHG emissions [131] and production of electricity that can be sold at a basic price of RM 0.32 up to RM 0.47 kW h<sup>−1</sup> under Renewable Energy Act 2011 [Act 725] [98] but also provides heat for drying EFB. Dried EFB can then be pyrolysed more economically and incorporated into soil as biochar during replantation supplemented with shredded OPT and OPF. Hansen et al. [47] carried out a life cycle assessment (LCA) on the enhanced used of oil palm residues, and identified total equivalent CO<sub>2</sub>-savings of 405 kg CO<sub>2,e</sub> t<sup>−1</sup> CPO for an EFB-biochar, yield-optimized pyrolysis process. The total attributional equivalent CO<sub>2,e</sub>-savings per t EFB comprise of 210 kg CO<sub>2,e</sub> for biochar, 234 kg CO<sub>2,e</sub> for bio-oil (replacing conventional diesel) and 29 kg CO<sub>2,e</sub> for syngas burned in gas turbines replacing conventionally produced electricity. Assuming that 75% of EFB are currently used for mulching in oil palm plantations [47] and 23 million t EFB yr<sup>−1</sup> are being produced (Section 2), a potential attributional equivalent CO<sub>2,e</sub> emission reduction of 3.6 million t CO<sub>2,e</sub> yr<sup>−1</sup> can be achieved if EFB is converted to biochar instead. This alone is potentially worth RM 60 million (RM 16.60 t<sub>CO<sub>2</sub></sub><sup>−1</sup> as of Feb. 2012) in avoided external costs [GenPower Carbon Solutions, pers. comm.]; an attractive green revenue remained notwithstanding the uncertain future of carbon market in the second period of the Kyoto Protocol.

In another paper investigating GHG emissions associated with land conversion to oil palm, Hansen et al. [99] recommended to increase the productivity of oil palm plantations in terms of FFB yield and to add biochar from oil palm residues to degraded land for regeneration instead of converting state forest reserves into plantation to satisfy the increasing demand for palm oil worldwide.

Wang et al. [100] studied the effects of co-produced biochar on life cycle GHG emissions of pyrolysis-derived renewable fuels and compared the GHG emissions for two scenarios in which biochar is either combusted to produce electricity or applied to soil to increase fertilizer efficiency, soil organic carbon, and crop yields as well as reduce N<sub>2</sub>O and CH<sub>4</sub> emissions from soils. The authors established that the overall attributional life-cycle GHG emissions for pyrolysis-based gasoline are lower when biochar is applied to soil than when it is combusted. Sensitivity tests revealed that biochar carbon content and yield exert the strongest influence on GHG emissions results, while biochar's ability to suppress N<sub>2</sub>O emissions and increase soil organic carbon were subject to high uncertainty.

It is recognized that the abundantly available oil palm biomass is versatile and competitive [101–102] as fertilizer supplement, and bioenergy and biomaterials production gearing towards reduction of cultivation cost, GHG emissions and increased sustainable development. In fact, the potential GHG emissions reduction of biochar ranged from 12 to 22% [96,103]. Although palm biomass-based biochar as soil amendment material provides huge opportunity cost as indicated by carbon credit and supported by Gaunt and Lehmann [96], the counterfactual of not doing the established alternatives might be an industry in which the potential use of oil palm biomass for the above applications be intensified, leaving behind certain percentage of it being ineffectively mulched. Contrarily, if other side-products of oil palm biomass become scarcer, diversifying biomass feedstock options is likely to happen in attempting to achieve a low carbon economy for the nation.

### 4.2. Biochar–soil interaction

The discovery of highly fertile and sustainable dark soils in the Amazon Basin, ancient Terra Preta de Indio has re-ignited the

interest of researchers from around the world to conduct investigations on biochar. Modern research has demonstrated that the porous structure coupled with a large surface area of many biochars [3,95,109] can promote plant growth by improving soil physical and chemical characteristics, such as water holding capacity [95,104], nutrient retention [95,105], pH [105–106] and cation exchange capacity (CEC) [106–107]. The effect of biochar as soil amendment is highly dependent on soil fertility and fertilizer management [108] as shown in Table 5 [110].

Biochar is most beneficial to crop growth and biomass production when applied to low fertility soil [111,112]. The beneficial effects of biochar depend on its interactions with soil, microbes, and plant roots. Reactions that may occur after the addition of biochars to soil include dissolution–precipitation, adsorption–desorption, acid–base, and redox reactions [113].

Numerous authors have demonstrated that certain biochars are able to adsorb ammonium [64,114,115], and reduce leaching of soil nutrients such as  $\text{NO}_3$  and  $\text{PO}_4$  [95,114,116–119]. Mukherjee and

Zimmerman [119] concluded that biochar should be chosen carefully for each given amendment project and suggested to use higher temperature or aged biochar in sandy soils because they have a lower tendency to release sudden pulses of nutrients. Sika and Hardy [116] observed that application of 2.5 and 10% pine wood slow pyrolysis biochar (450 °C) to sandy soil led to over-liming raising some concerns regarding the practical use of biochar in improving N fertilizer-use efficiency of plants. Zheng et al. [117], on the other hand, suggested that addition of up to 5% slow pyrolysis giant reed grass biochar to soil (29% sand content) could reduce N leaching and increase N retention and bioavailability in agricultural soils and thus potentially decrease the N fertilizer demand for maize crop growth.

Cayuela et al. [120] studied the interaction of nine different, slow pyrolysis 500 °C biochars with the N cycle in 14 different soils and proposed that biochar facilitates the transfer of electrons to soil denitrifying microorganisms, which together with its liming effect and high surface area promotes the reduction of  $\text{N}_2\text{O}$  to  $\text{N}_2$ .

**Table 5**

Summary of studies on biochar used as a soil amendment ([110] and references therein).

| Author(s)   | Location                             | Soil type                             | Type of biochar                            | Biochar application rate ( $\text{t ha}^{-1}$ )   | Crop   |
|---|--------------------------------------|---------------------------------------|--|---|--|
| Kishimoto and Sugiura (1985)  | Japan                                | Volcanic ash soil, loam               | Unknown wood                               | 0, 0.5, 5.0 and 15.25   | Soybean  |
| <b>Crop response:</b> At $0.5 \text{ t ha}^{-1}$ , increased yield by 51 %. At $5 \text{ t ha}^{-1}$ and $15.25 \text{ t ha}^{-1}$ , reduced yield by 37 % and 71 % respectively, due to micronutrient deficiency induced by an increase in pH.   |                                      |                                       |  |   |  |
| Mikan and Abrams (1995)   | Pennsylvania, United States          | Forest area on relic charcoal hearths | Wood for charcoal production               | –   | Vegetation in hearth and non-hearth areas compared after 110 years |
| <b>Crop response:</b> Tree density and basal area were reduced by 40%.  |                                      |                                       |  |   |  |
| Young et al. (1996)   | Appalachian mountains, United States | Forest area on relic charcoal hearths | Wood for Charcoal production               | –   | Trees  |
| <b>Crop response:</b> The richness and diversity of overstory and understory tree cover as well as ground vegetation were consistently lower on hearths than on adjacent, non-hearth areas.   |                                      |                                       |  |   |  |
| Glaser et al. (2002)  | Brazil                               | Xanthic ferralsol                     | Secondary forest wood                      | 0, 68 and 136.75  | Rice, cowpea   |
| <b>Crop response:</b> At application rate of $68 \text{ t ha}^{-1}$ , biomass of rice and cowpea increased by 20% and 50% respectively, compared to the control treatment with no biochar applied. At application rate of $136.75 \text{ t ha}^{-1}$ , biomass of cowpea increased by 100%.   |                                      |                                       |  |   |  |
| Steiner (2006)  | Brazil                               | Xanthic ferralsol                     | Wood                                       | 11.25   | Banana   |
| <b>Crop response:</b> Reduced soil acidity and increased potassium uptake.  |                                      |                                       |  |   |  |
| Yamamoto et al. (2006)  | Indonesia                            | Acid soil                             | Bark                                       | 15.25   | Maize  |
| <b>Crop response:</b> Higher yields with biochar and fertilizer compared to fertilizer alone.   |                                      |                                       |  |   |  |
| Steiner et al. (2007)   | Brazil                               | Xanthic ferralsol                     | Secondary forest wood                      | 11.25   | Rice, sorghum  |
| <b>Crop response:</b> Charcoal plus mineral fertilizer improved grain yield by a factor of 1.5–2 and improved stover by a factor of 1.3–1.4, while by adding in compost, yields were consistently greater (4–12 times greater) compared to using fertilizer alone.  |                                      |                                       |  |   |  |
| Van Zwieten (2007)  | Australia                            | Semi-tropical soil                    | –  | 10  | Wheat, soybeans  |
| <b>Crop response:</b> Biomass of soybeans was more than doubled while wheat was tripled. Percentage increase in biomass was the same when nitrogen fertilizer was applied together with biochar. Biochar raised soil pH at about 1/3 the rate of lime.  |                                      |                                       |  |   |  |
| Van Zwieten et al. (2007)   | Australia                            | Ferralsol                             | Paper mill sludge                          | 10  | Wheat  |
| <b>Crop response:</b> 30–40 % increase in wheat height in acidic soil but not in alkaline soil.   |                                      |                                       |  |   |  |
| Collins (2008)  | Washington                           | Quincy sand, hale silt loam           | Peanut hull (PH), fir bark (SB)            | 0, 12.5, 25 and 50  | Wheat  |
| <b>Crop response:</b> In Quincy sand, the root-shoot ratio of wheat decreased in all application rates of biochar. In hale silt loam, the root-shoot ratio of wheat decreased at $25 \text{ t ha}^{-1}$ of PH biochar applied compared to nil (no change at 12.5 and $50 \text{ t ha}^{-1}$ ), while the root-shoot ratio of wheat increased in all SB biochar treatment. Soil pH increased 0.5–1 unit due to biochar addition. |                                      |                                       |  |   |  |
| Chan et al. (2008)  | Australia                            | Alfisol                               | Poultry litter                             | 0, 10, 25.25, 50.5  | Radish   |
| <b>Crop response:</b> Yield increased from 42–96% at $10$ – $50.5 \text{ t ha}^{-1}$ of biochar, relative to the yield from unamended control.  |                                      |                                       |  |   |  |
| Van Zwieten et al. (2008)   | Australia                            | Ferralsol                             | Poultry litter (PL), paper mill waste (PM) | Maize: $0.5$ – $50.5 \text{ t ha}^{-1}$ PL biochar. Beans: $10 \text{ t ha}^{-1}$ PL and PM biochar versus $3 \text{ t ha}^{-1}$ lime | Maize, faba beans  |
| <b>Crop response:</b> 51 % yield increase at $10 \text{ t ha}^{-1}$ and 109% yield increase at $50.5 \text{ t ha}^{-1}$ for maize planting compared to nil. Beans yields were the highest with biochar plus fertilizer compared to biochar alone. PL biochar outperformed lime amendment.   |                                      |                                       |  |   |  |

However, the findings are based on short-term (30 d) laboratory assays that did not take into account field conditions such as biochar ageing or soil–plant–microbe interactions.

Fang et al. [121] incubated wood-based slow pyrolysis biochars (450 or 550 °C) in four soils (Inceptisol, Entisol, Oxisol and Vertisol) at 20 and 40 °C and monitored the mineralization of biochar–C over a period of 12 months. The authors found that C mineralization of the 450 and 550 °C biochars was least in the Oxisol and greatest in the Inceptisol suggesting that biochar–C was stabilized by variable charge minerals in the Oxisol. Similar findings on biochar stabilization were observed by Bruun et al. [122] who elucidated the role of clay, microorganisms and carbonates on CO<sub>2</sub> emissions from slow-pyrolysis, <sup>14</sup>C-labeled barley roots biochar in low, intermediate and high clay soils.

#### 4.3. Major challenges to promote biochar in Malaysia

Promotion of oil palm biomass derived biochar in Malaysia faces numerous challenges ranging from economical and environmentally-friendly production, lack of quantitative understanding of the impact of biochars on soil fertility, soil biota, water holding capacity, FFB yield, GHG emissions from pyrolysis plants and plantation, pest control, and to factors influencing its long-term stability under field conditions.

Even though there is surplus amount of oil palm biomass that can be used as feedstock, the physicochemical nature of the biomass [123] itself is still an important barrier to develop biochar production. In practice, not all of these residues can be used as feedstock due to technical constraints and ecosystem functions. For instance, leaving behind certain amounts of OPF and OPT in the plantation protect soil quality and helps to reduce the need for inorganic fertilizers [29,124]. Besides, oil palm biomass contains moisture to some substantial extend [41] due to water uptake during plant growth, thus transporting wet biomass from the source to the production site becomes energetically unfavorable and costly with increasing distance [102,123]. The high moisture content of oil palm biomass waste, especially EFB after steam-sterilization [101], requires drying to prevent biodegradation and loss of heating value [125]. As such, besides normal pre-treatments such as chopping, shredding and grinding [126], additional drying process prior to pyrolysis process, not only increases the production cost but also in equipment's investment [56,102]. In order to keep cost at a minimum, a system-integrated approach is needed [127] in which, for example, waste thermal energy sources are identified within a palm oil mill (e.g., waste heat of combustion gases from POME-derived biogas) and utilized in other, thermal-energy driven operations (e.g., drying of EFB).

Another important barrier for the development of biochar production by independent producers is the lack of long-term contracts with oil palm biomass suppliers in the market. The supply chain between the oil palm biomass owners, producers (technology providers), investors and the potential users have not been technically and commercially developed and demonstrated in a holistic manner. For the biomass end users and producers, it is virtually impossible to get contracts for consistent feedstock supply from palm oil mills and oil palm plantations. Short term delivery agreements can be made, but long term arrangements for securing supply in reasonable price are very difficult [102,128]. Unless an integrated approach is sought, most of the generated oil palm biomass is scattered and far from easy reach for utilization [101,123,126]. Thus, there is a need to set up a biomass collection centre – an area very appropriately associated with and initiated in current biomass business environment but none has yet to succeed – to facilitate and reduce the collection time and logistics cost [102,123,129]. A covered yard is necessary to supply a constant amount of oil palm biomass. Storage time should

however be short, for example 5 days, as the biomass even with 45% of moisture is still very vulnerable to natural decay through fungi or bacterial processes. This gives handling and health problems due to fungi spores, but it also contributes through a loss of dry matter through biological degradation [101].

Regardless of the benefits of biochar application, public and market acceptance are critical in supporting and sustaining the biochar production. Government should offer tax incentives or appropriate financing [128,130] for biochar producers to set up capital intensive, industrial-scale pyrolysis systems, facilitate the carbon credit trading scheme and to diminish the fear due to a limited profit from a perceived risky new business where bio-oil and syngas from the same pyrolysis system are more profitable in terms of energy uses. Also, there is a need to increase the demand and acceptance of the biochar in the local market by promoting sustainable agriculture and developing standards and conformity assessment tool [102,129]. It is equally important to set up appropriate infrastructure to educate the public and farmers [128,130] of the benefits of biochar management in agriculture. The conversion technology available to produce biochar in sustainable manner is also crucial as most of the existing technologies or those in the making require high investment cost [126,130]. There is a need to gear towards innovating technologies with reduced capital cost which provide integral solution in managing and utilizing the co-products/by-products generated [102].

## 5. Conclusion

The science of biochar production and application has made rapid progress in the past few decades worldwide. However, industrial-scale pyrolysis of biomass for biochar production in general, and Malaysia in particular, is still in its early stage of development. However, the acceptance towards biochar is easier if there are clear economic incentives and benefits from the systematically organized biochar management. The thermochemical process has strong adaptability to biomass resources, especially with abundant oil palm biomass available in the country. It is clear that biomass conversion and sequestration projects have the potential to contribute significantly to climate change mitigation. In addition, producing biochar from oil palm biomass provides promising co-benefits, including the generation of renewable electricity, liquid biofuels, gas biofuels, large amounts of heat or low pressure steam, and the potential of a net withdrawal of carbon dioxide from the atmosphere. In the future, biochar, standing by its own, is not enough to reduce GHG to manageable safety level, but it can be among the options big enough, implemented and integrated together among the palm oil-producing countries with many different approaches, to promise a major positive impact in the challenges to combat climate change and crop productivity.

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